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LBL-34060
UC-406

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November 1993

This work was supported by the Director, Office of Energy Research,
Office of Biological and Environmental Research, Structural Biology Division,
of the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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A High Rate, Low Noise, X-Ray Silicon Strip Detector System

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Abstract

An x-ray detector system, based on a silicon strip detector wire-bonded to a low noise charge-sensitive amplifier integrated circuit, has been developed for synchrotron radiation experiments which require very high count rates and good energy resolution. Noise measurements and x-ray spectra were taken using a 6 mm long, 55 μm pitch strip detector in conjunction with a prototype 16-channel charge-sensitive preamplifier, both fabricated using standard 1.2 μm CMOS technology. The detector system currently achieves an energy resolution of 350 eV FWHM at 5.9 keV, 2 μs peaking time, when cooled to -5°C .

I. INTRODUCTION

Many synchrotron radiation experiments could greatly benefit from improved detector instrumentation offering both good energy resolution and high count rate capability. These two attributes are typically directly coupled and detector systems currently available often stress one while compromising the other [1,2]. In pursuit of the goal of a detector with good energy resolution, high count rate capability and position sensitivity, we report on the development of an x-ray detector system based on a multi-element linear silicon strip detector in conjunction with a multi-channel low noise charge-sensitive preamplifier. Both the detector and preamplifier are based on CMOS integrated circuit technology and were adapted from existing designs originally intended for high energy physics particle detection [3] and PET (positron emission tomography) signal processing [4], respectively. In this application, the detector segmentation and small element area are not specifically intended to derive position information (although it certainly can be used as such), but to offer the following advantages:

- low detector capacitance to reduce the noise contribution of the preamplifier,
- reduced leakage current per detector strip to diminish shot noise,

- increase in total count rate capability by utilizing a short peaking time and distributing the total flux over many channels.

The low total input capacitance of the detector plus preamplifier results in very good energy resolution and allows the use of short shaping times, and hence high count rates. Very high total count rates can be handled by parallel processing and digitizing the signals from all the detector elements. Although a generic multi-element Si detector and readout electronics could be used for a number of different applications, the system we have initially designed is geared toward a specific fluorescence EXAFS (extended x-ray absorption fine structure spectroscopy) application, which involves the detection of the L-shell fluorescence from uranium in organic complexes [5]. This particular application requires an energy resolution of approximately 350 eV FWHM at 17 keV, and a count rate capability of $\sim 10^6$ counts per second, which is well within the reach of this prototype device. The detector and preamplifier are described; noise measurements and the x-ray response of the detector system are shown.

XBL 907-6464A

Fig. 1 Silicon strip detector cross-section.

II. DETECTOR AND PREAMPLIFIER IC

A schematic of the detector cross-section is shown in Fig. 1. The detectors were fabricated on high resistivity ($\sim 6 - 8 \text{ k}\Omega\text{-cm}$) n-type silicon, 300 μm thick. The detector is segmented into 96 strips by the 15 μm x 6 mm boron-implanted areas, on a 55 μm pitch. The backside n⁺ contact consists of a 1.2 μm thick phosphorous-doped polysilicon layer which produces very low leakage devices. (The detector fabrication procedure has been previously described and will not be detailed here [6]). The capacitance and the leakage current at room temperature, per strip, are $\sim 0.6 \text{ pF}$ and $\sim 15 \text{ pA}$, respectively. The detector dimensions and geometry are matched to our EXAFS application, but modifications of the detector geometry are possible for detector optimization for other applications.

¹ The authors would like to thank Steve Holland and Nick Palaio for fabrication of the detectors. This work was supported by the Director, Office of Energy Research, Office of Biological and Environmental Research, Structural Biology Division, of the U.S. Department of Energy under Contract No. DE-AC0376SF00098, and also by the Director of the Engineering Division of Lawrence Berkeley Laboratory. Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

The preamplifier chip was adapted from an existing design for HEP applications that was modified for APD readout in positron emission tomography [4]. The 16-channel integrated circuit was fabricated using standard 1.2 μm CMOS technology. Each channel contains a low noise high gain charge-sensitive preamplifier followed by a simple active filter that provides a variable CR-RC shaping function. The circuit was laid out with a 100 μm channel-to-channel pitch originally designed to match a 100 μm pitch detector. The layout can be adapted easily to a 50 μm pitch. The die size of 2 x 2 mm^2 is larger than required, but is the minimum size allowed by the manufacturer.

Fig. 2 Preamplifier and shaper circuit diagram.

A simplified schematic of a single preamplifier channel is shown in Fig. 2. The integrator is configured as a single stage common-source cascode amplifier with a cascode active load. The feedback capacitance of 20 fF (C_f) provides a gain of 50 mV/fC. The size of the input device (M1) was optimized for a detector capacitance of 0.7 pF plus 0.3 pF for the bonding pads and stray capacitances and has a gate length of 1.2 μm and a width of 500 μm . A p-channel input transistor rather than an n-channel device was selected for the input device because of its superior noise characteristics. For this process, the p-channel transistor exhibits somewhat lower noise in the white noise regime and, more importantly, much lower excess noise in the low-frequency "1/f" regime. The devices used here do not show a classic 1/f noise spectrum at low frequencies, but a much weaker noise increase that cannot be characterized by a single slope. An important parameter for the preamplifier noise is the bias current in the input device. To preserve full control of the bias current, it is set externally through a current mirror (IM1) common to all channels on the chip. "Active" cascode circuits are used to provide a very high open-loop gain, in excess of 100 dB. Baseline recovery after signal integration is achieved by a low-frequency feedback loop using a differential amplifier (M9, M10) that forces the output of the integrator to a reference voltage (v_{ref1}) that is generated on-chip. This feedback network introduces a differentiation with a variable time constant and it is controlled via a current mirror (Idiode) common to all channels. In principle this current

should be set as low as possible (a few pA) as it contributes shot noise to the integrator. However, this current also supplies the dark current to the detector, and its value is determined by the detector current.

The shaper amplifier circuit is similar to the integrator. An n-channel common-source transistor is chosen over a p-channel device because its transconductance is larger in strong inversion and noise is not critical at this stage. Rise and fall times are controlled via current mirrors (I_{rise} , I_{reset}) common to all channels, resulting in a variable shaping time from 500 ns to 50 μs . The unfiltered voltage gain of the second stage is given by $C_{s2}/C_{f2} = 12.5$. Together the two amplification stages on the chip provide a high gain of 100 mV/1000 electron step response to override possible noise pickup in signal transmission to the external electronics. Two input lines coupled to the amplifier inputs by $C_{cal} = 80$ fF are provided for testing and calibration purposes.

Fig. 3 Detector and preamplifier in the test setup. The size of the integrated circuit die is about 2 mm x 2 mm. For testing purposes various groups of strips were wire-bonded to the amplifiers.

III. SYSTEM CHARACTERISTICS

Figure 3 is a photograph of the detector wire-bonded to a preamplifier chip for test purposes. Noise measurements were made at -5° C and at room temperature, to determine the preamplifier contribution to the noise for a range of external capacitors, and the preamplifier plus detector noise as a function of peaking time. All measurements shown here were

made using a Tennelec TC 224 amplifier for Gaussian pulse shaping, and not using the on-chip shaping network which will be utilized in the final detector system.

To measure the noise increase with external input capacitance, chip capacitors were wire-bonded to the preamplifier inputs. As is shown in Fig. 4 the noise increases linearly with the added capacitance. Fitting the data in Fig. 4 gives the following expression for the equivalent noise charge (ENC) at 1 μ s peaking time:

$$\text{ENC} = 29 \text{ [rms electrons]} + 26 \text{ [rms electrons / pF]} \times C \quad (1)$$

From this equation the combined capacitances of the input device, bonding pads, and strays is estimated to be ~ 1.1 pF.

Fig. 4 Noise as a function of external capacitance for 1 μ s peaking time.

Fig. 5 Noise as a function of peaking time for a preamplifier channel with open input, with external capacitances of 0.38 pF and 0.75 pF, and for detector strips at -5°C and at 22°C .

In Fig. 5, the noise as a function of peaking time is compared for a preamplifier with open input, two external capacitances, and a preamplifier plus detector, all at -5°C . At short peaking times ($< 1 \mu\text{s}$) the noise is dominated by the preamplifier's equivalent noise voltage. In this region the noise of the strip detector lies between the noise of the 0.38 pF and 0.75 pF capacitors suggesting a detector capacitance of ~ 0.6 pF. For peaking times longer than $2 \mu\text{s}$ the shot noise contribution of the detector leakage current becomes increasingly significant, resulting in a minimum noise at $4 \mu\text{s}$ for the cooled detector. Also shown in Fig. 5 is the noise as a function of peaking time for the detector at room temperature. At room temperature the noise due to the detector leakage current is important for all but the shortest peaking times and causes the noise minimum to shift to $1.5 \mu\text{s}$. As can be seen in Fig. 5, cooling the detector to a temperature below 0°C reduces the noise contribution of the detector leakage current to an insignificant level for peaking times shorter than $2 \mu\text{s}$. It is noted that there is an uncertainty in the absolute noise values shown in the figures due to the uncertainty in the value of the test capacitor C_{cal} on the IC chip.

Fig. 6 ^{55}Fe spectra for strip detector illuminated through the back and the strip side, $2 \mu\text{s}$ peaking time, -5°C .

Figure 6 shows the spectral response of a single detector strip to an ^{55}Fe source at -5°C and $2 \mu\text{s}$ peaking time, illuminated through the strip side and the back side. The $\text{Mn } K_\alpha$ and K_β peaks are clearly resolved, with an energy resolution of ~ 350 eV FWHM at 5.9 keV. This is approximately 25 eV higher than the calculated value based on the noise measurements of Fig. 5. Further measurements are required to resolve this discrepancy. To the best of our knowledge, this is by far the lowest noise achieved by a silicon strip detector with an IC preamplifier chip, to date [7,8]. The energy resolution of the detector, whether irradiated through the front or back, is practically identical, but there is a clear difference in the background below the main peaks. The strip side response has a lower background, but exhibits two anomalous peaks: one at ~ 4 keV

and one at very low energy. The 4 keV peak is attributed to incomplete charge collection in the weak field regions between strips. The intensity of the ~4 keV peak decreases with increasing bias voltage, but never completely disappears before the bias causes breakdown of the device. (Very similar effects have been seen in low temperature Si(Li) detectors, again with the anomalous low energy peak due to incomplete charge collection in weak field regions in the device [9]). The back side response exhibits no anomalous peaks but an enhanced background. Given that the absorption length for 6 keV x-rays is of the order of 20 μm , the weak field regions between the strips have a negligible effect on charge collection when irradiating through the back side, but charges generated near the surface can be trapped in the polysilicon layer causing the enhanced background.

Fig. 7 shows an ^{241}Am spectrum collected by illuminating the strip side of the detector. The spectrum resulting from back side illumination (not shown in the figure) is indistinguishable at all but the lowest energies where it exhibits a slightly enhanced background. Since the higher energy x-rays of the ^{241}Am source get absorbed throughout the detector volume, neither the weak field regions between the strips nor the possible charge trapping in the polysilicon layer is as important as in low energy x-ray detection.

Fig. 7 ^{241}Am spectrum, strip side illumination.

IV. DISCUSSION

The prototype strip detector and IC preamplifier system currently achieves an energy resolution of ~350 eV FWHM at 5.9 keV, 2 μs peaking time and -5° C. To reduce the noise further and improve the energy resolution, the detector capacitance and leakage current must be reduced, and so the next set of detectors will be designed with shorter strips. Modification of the preamplifier to match the lower capacitance is straightforward. With the smaller detector the stray capacitance due to wire bonding becomes significant. Monolithic integration of the detector and preamplifiers would practically eliminate the

additional stray capacitance. This technology has already been demonstrated [10] and will also be considered for future developments of this system. We are currently developing the readout electronics and data acquisition hardware to accommodate a 64-channel detector. Four 16-channel preamplifier chips will be wire-bonded to 64 strips, followed by pulse processing in amplifier modules designed at LBL (eight amplifiers per single width CAMAC module) with selectable gains and adjustable discriminator thresholds for gate generation. The signals will be digitized by 64 ADC modules (again, eight modules per single CAMAC width) which feature a 3 μs conversion time and independent input gates for each channel. The x-ray spectra will be accumulated in histogramming modules connected to the ADCs through FERAbus and read out using CAMAC and a Macintosh PC utilizing KMAX² software. The system is designed to handle up to 100 kHz/channel, well above the count rate limitations imposed by pile-up and energy resolution requirements. This first generation of detector and readout will be used in a fluorescence EXAFS study of uranium in soluble organic complexes. Future modifications of the detector and readout electronics will be made to accommodate other applications.

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